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Ordering of dust particles in dusty plasmas under microgravity

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Structure formation of dust particles in dusty plasmas under microgravity has been simulated by the molecular dynamics method. It is shown that, at low temperatures, dust particles are organized into layered spherical shells. The number of shells is a function of the system size and the strength of screening by ambient plasma particles, while the dependency on the latter is much weaker. In the simulation, the condition of the charge neutrality satisfied by the system of dust particles and plasma particles is properly taken into account.

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The system of macroscopic (micron-sized) dust particles immersed in ambient plasma provides us with a clear example of a strongly coupled system due to large negative charge on the particles [1]. Lattice structures and dynamics of dust particles have been observed directly by charge-coupled device (CCD) cameras and naked eyes. On the other hand, structures and dynamics are strongly affected by the gravity on earth due to large masses of macroscopic dust particles: Typical structures are characterized by layers with normals along the direction of gravity [2]. The experiments under the condition of microgravity are thus expected to elucidate intrinsic properties of dusty plasmas which are not directly related to the effect of gravity.

In an experiment on dusty plasmas under microgravity, the geometry of the system is determined by the parallel plate structure and the void has been observed [3]. As for the possible cause of void, such as thermophoretic force due to inhomogeneity in temperature or ion flow, more investigations seem to be needed. The most important characteristic of the systems under microgravity, however, may be the isotropy of the environment which is not realized on earth. Therefore, we assume here that the system is homogeneous, isotropic, and free from the ion flow, and analyze the structure formation of dust particles under the condition of microgravity. The results will be useful as a reference when we take the effects of thermophoretic force, ion flow, or others into account.

We consider a system in a volume V composed of N_d dust particles, N_i ions, and N_e electrons and denote the charges of dust particles, ions, and electrons by $-Qe$, e, and $-e$, respectively. We assume that the system satisfies the condition of the charge neutrality

$$(-Qe)n_d + (-e)n_e + en_i = 0, \tag{1}$$

where $n_d = N_d/V$, $n_i = N_i/V$, and $n_e = N_e/V$ are the densities of components.

When we take a statistical average over electron and ion degrees of freedom in the adiabatic approximation and neglect the effect of electron-electron, electron-ion, or ion-ion correlation, we arrive at the Yukawa system as a model for dust particles in dusty plasmas [4]. The Helmholtz free energy of the system of dust particles is then given by

$$U_{\mathrm{coh}} + U_{\mathrm{sheath}}, \tag{2}$$

where

$$U_{\mathrm{coh}} = \frac{1}{2}\sum_{i\neq j}^{N_d} v(r_{ij}) - 2\pi N_d n_d \lambda^3 \frac{(Qe)^2}{\lambda}, \tag{3}$$

$$U_{\mathrm{sheath}} = -N_d \frac{1}{2}\frac{(Qe)^2}{\lambda}, \tag{4}$$

and $v(r)$ is the Yukawa potential

$$v(r) = \frac{(Qe)^2}{r}\exp(-r/\lambda). \tag{5}$$

The parameter λ characterizes the screening by electrons and ions and is given by

$$\frac{1}{\lambda^2} = \frac{4\pi n_e e^2}{k_B T_e} + \frac{4\pi n_i e^2}{k_B T_i}, \tag{6}$$

where T_i and T_e are the temperatures of ions and electrons, respectively. The latter temperatures are usually different from (higher than) that of dust particles T_d.

In U_{coh} given by Eq. (3), the second term is the internal energy for uniformly distributed Yukawa particles:

$$2\pi N_d n_d \lambda^3 \frac{(Qe)^2}{\lambda} = N_d \frac{n_d}{2}\int d\mathbf{r}\, v(r). \tag{7}$$

In other words, U_{coh} *reduces to zero when dust particles are randomly distributed without correlation*.

From the Poisson equation, the charge density $\rho(r)$ responsible for the screening of the Yukawa potential is calculated as

$$4\pi\rho(r) = -\,\mathrm{div}\,\mathrm{grad}\left[-\frac{Qe}{r}\exp(-r/\lambda)\right] = \frac{1}{\lambda^2}\frac{Qe}{r}\exp(-r/\lambda). \tag{8}$$

The work which is necessary to form sheaths around N_d dust particles with the charge $-Qe$ is thus given by

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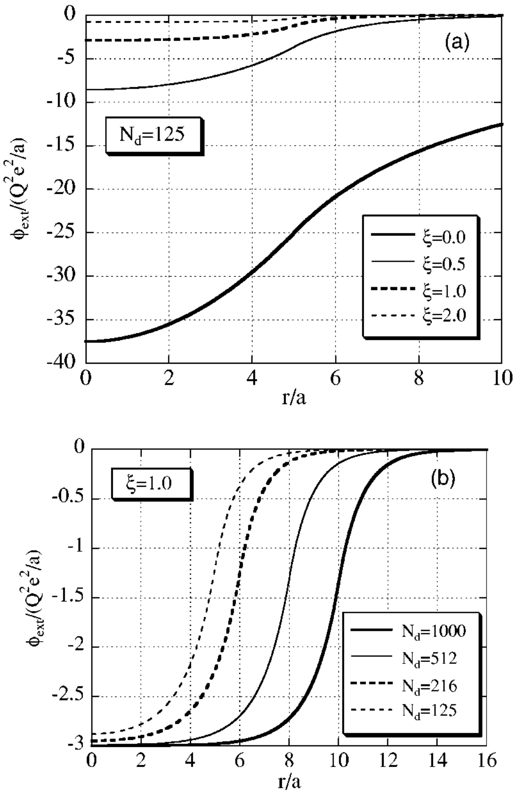

FIG. 1. (a) Potential field for 125 Yukawa particles with $\xi=0$, 0.5, 1, and 2 with $R/a=N_d^{1/3}=5$. (b) The same as (a) for 125, 216, 512, and 1000 particles with $\xi=1$, R/a being 5, 6, 8, and 10, respectively.

$$N_d\frac{1}{2}\int d\mathbf{r}\rho(r)\left(-\frac{Qe}{r}\right)=-\frac{N_d}{2}\frac{(Qe)^2}{\lambda}, \tag{9}$$

which is equal to Eq. (4). Here, the factor $1/2$ comes from the linearity of the relation between $-Qe$ and ρ in the charging process. The term U_{sheath} is thus the free energy of the sheath around dust particles. Note that this energy is independent of the correlation between dust particles and can be neglected when analyzing the structure of dust particles.

In what follows, we assume that the volume V is determined by some experimental condition, such as the configuration of electrodes and other geometries. Under the condition of microgravity, we may assume that the volume takes the form of a sphere of radius R due to isotropy.

In order to simulate the system in a sphere of volume V whose potential energy is given by Eq. (3), we introduce the (imaginative) uniform negative charge density which neutralizes that of dust particles: We note that the second term on the right-hand side of Eq. (3) corresponds to the interaction with this uniform negative Yukawa charge density which cancels the first term for randomly distributed dust particles. The potential due to the neutralizing negative charge is given by

$$\phi_{\text{ext}}(r)=-n_d(Qe)^2\int_{r'<R}d\mathbf{r}'\frac{1}{|\mathbf{r}-\mathbf{r}'|}\exp(-|\mathbf{r}-\mathbf{r}'|/\lambda) \tag{10}$$

and is calculated as

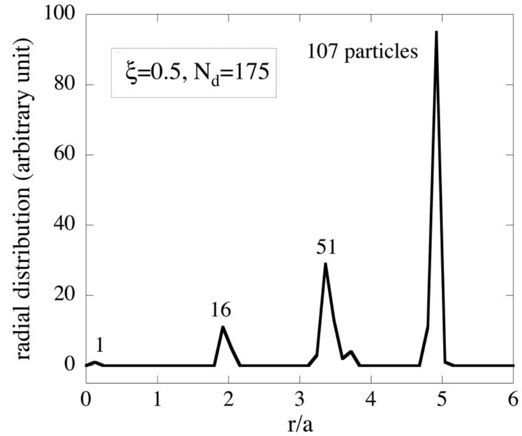

FIG. 2. Distribution of particles as a function of the distance from the center. Parameters are $\xi=0.5$ and $N_d=175$.

$$\phi_{\text{ext}}(r)=4\pi n_d(Qe)^2\lambda^2\left[1-\frac{\lambda}{r}\exp(-R/\lambda)\left(1+\frac{R}{\lambda}\right)\sinh\left(\frac{r}{\lambda}\right)\right],\quad r<R, \tag{11}$$

$$=4\pi n_d(Qe)^2\lambda^2\frac{\lambda}{r}\exp(-r/\lambda)\times\left[\frac{R}{\lambda}\cosh\left(\frac{R}{\lambda}\right)-\sinh\left(\frac{r}{\lambda}\right)\right],\quad r>R. \tag{12}$$

The values of the potential are plotted in Fig. 1 for some cases of N_d and $\xi=0$, 0.5, 1, and 2 where $\xi=a/\lambda$ is the ratio of the mean distance $a=(3/4\pi n_d)^{1/3}$ to λ.

When the spherical volume V is determined externally, we simulate the structure of dust particles as a system of Yukawa particles interacting via Eq. (5) in the potential $\phi_{\text{ext}}(r)$. The potential energy part of the Hamiltonian then takes the form

$$\frac{1}{2}\sum_{i\neq j}^{N_d}v(r_{ij})+\sum_{i=1}^{N_d}\phi_{\text{ext}}(r_i). \tag{13}$$

For this system, we have three dimensionless parameters which may be taken as the total number of dust particles N_d,

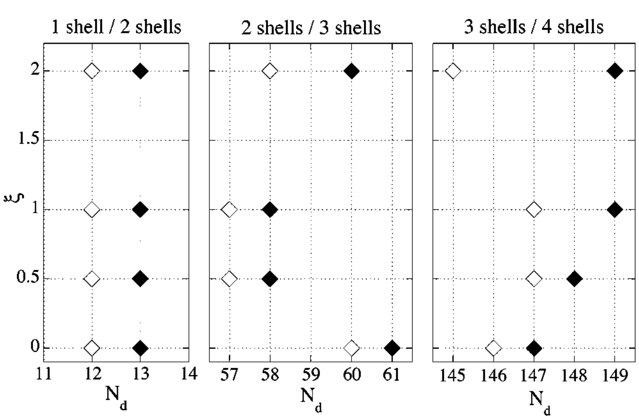

FIG. 3. Transition in number of shells. To the left of open marks, structures with smaller number of shells have lower energy and, to the right of filled marks, the ones with larger number of shells have lower energy. The distinction is not clear in between.

$\Gamma=(Qe)^2/ak_BT$, and ξ. In the limit of high temperatures, the structure may be the uniform distribution in the volume V. With the decrease of the temperature, there appears the correlation and finally we expect to have a solidlike structure of finite extension. In this article, we are interested in structures at low temperatures where our system has two characteristic parameters, N_d and ξ.

Applying the molecular dynamics, we have analyzed the structures of dust particles at low temperatures: Starting from some configurations, we anneal the system for a sufficiently long time and slowly cool the system. With the decrease of the temperature, we observe clear shell structures. An example of the resultant radial distribution is given in Fig. 2.

The number of shells is determined by parameters N_d and ξ. The dependency on these parameters is shown as a phase diagram for the structure in Fig. 3, where the case of Coulomb interaction with $\xi=0$ [5,6] is also shown.

As is shown in Fig. 3, the number of shells and the positions of shells are not very sensitive to the strength of screening ξ, implying that the structure does not strongly depend on ξ. We may interpret this independence as follows: In the shell structure, the intershell distance is nearly equal to the intrashell mean distance and the change in the mutual interaction does not affect the structure as a whole so long as it is isotropic.

Recently, dust Coulomb balls have been observed in experiments on the ground where the gravity is balanced by thermophoretic force [9]. In these balls, dust particles form spherical shell structures and 190 dust particles are organized into 4 shells. This is consistent with our result.

When we increase the system size, we eventually have the system whose main part is organized in the lattice structure of an infinite Yukawa system [7]. In between, one expects the critical system size to exist for the structural transition from the shell structure. In the case of $\xi=0$, the critical value is determined as 1.1×10^4–1.5×10^4 [8]. The critical system size for the case of finite ξ is not known.

In conclusion, we have obtained the structure of dust particles at low temperatures under the condition of microgravity where there is no specified direction in space. This structure is in sharp contrast with that under the gravity on earth where we have one-dimensional structures characterized by the total area density and the strength of screening [2].

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